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Handling the complexities of real-life job shops when implementing workload control: A decision framework and case study

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Abstract

The Workload Control (WLC) literature highlights the importance of balancing the shop floor workload, but also acknowledges that this can conflict with processing the most urgent orders – hence, there is a trade-off. In practice, shops contain many complexities, e.g. simultaneous batching and sequence-dependent set-up times that may conflict with processing the most urgent orders and require other solutions than workload balancing to avoid capacity losses. This adds to the trade-off dilemma, which traditionally only considers timing and balancing.

This paper develops a framework that determines whether to address a complexity through order release or dispatching. It comprises two dimensions: (i) the typical position of a complexity in the routing of an order; and (ii) the criticality of the complexity. A case study is presented, which demonstrates the framework's utility and illustrates the development of specific solutions designed to handle the complexities. Most complexities present in the case require handling at the order release stage. The challenges of handling multiple complexities at this decision level are evaluated. Finally, the implications for managers and future research are outlined.

Keywords: *Workload control; Order release; Job shop; Case study; Input control.*

1. Introduction

Make-to-order (MTO) companies only produce products after a customer order has been confirmed. This allows for a greater degree of customisation to be offered, which can lead to high variety and large variations in routings, processing times and set-up times (Stevenson et al. 2005). This context makes production planning and control (PPC) challenging (Hendry and Kingsman 1989), with the Workload Control (WLC) concept considered the most suitable solution for high-variety job shops producing customised products on a MTO basis (Stevenson et al. 2005). WLC is based on the concept of input/output control (Wight 1970), where the input rate of work to the shop is controlled in accordance with the output rate. There are three input control levels: job (or order) entry, job release and priority dispatching on the shop floor. Orders arriving at the shop do not enter the shop floor directly; instead,

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they are held in a pre-shop pool and released onto the shop floor in accordance with work centre norms or limits (Hendry and Kingsman 1991, 1993). The aim is to ensure that orders are released in time to meet their due dates, whilst avoiding backlogs and utilising work centre capacities effectively (Fredendall et al. 2010). Hence, both timing and workload balancing functions have to be considered simultaneously at the time of order release (Land 2004). However, these two functions often contradict, meaning that a trade-off decision has to be made between balancing the workload and prioritising the most urgent orders. If managed successfully, queues on the shop floor can be controlled and stabilised, making shop floor throughput times predictable. Once released, orders progress through the shop and the short queues can be handled by a simple dispatching rule (Kingsman 2000), although it may be necessary to update dispatching priorities once orders have been released (Land et al. 2014). Output control determines when an order leaves the queue, shop floor or system (Kingsman and Hendry 2002). The output rate can be increased by manipulating capacity; for example, by reallocating operators or using overtime.

In theory on order release, load balancing in particular has been shown to be important for realising good delivery performance – by allowing for short queues on the shop floor without a fall in output (Thürer et al. 2015). But in practice, shops contain many complexities, including sequence-dependent set-up times, batching and nesting that lead to orders having to be combined or having to follow a certain sequence. These factors impose additional restrictions on release if long queues of orders waiting for others without causing output losses due to the inefficient use of resources are to be avoided. As a consequence, it becomes necessary to look beyond managing the two-dimensional trade-off between the timing and workload balancing functions. Beyond release, dispatching rules should help to guarantee the right combination or sequence of orders on the shop floor. Few papers in the WLC literature consider practical complexities (Thürer et al. 2011; Hendry et al. 2013), meaning there remains a need to understand where and how they can be handled within order release and dispatching decisions. More generally, it is widely acknowledged that there is a need to conduct more empirical research that aims to improve practical implementations of the WLC concept (Stevenson et al. 2011).

In light of the above, this paper presents a combined theoretical and empirical study into the practical complexities of real-life job shops that hinder the reduction of workload without incurring a loss of output. It develops a framework to help practitioners decide *where* to accommodate complexities and evaluates the framework by applying it to a case study company. The case study also provides in-depth insights into *how* complexities can be

handled within the framework. The framework represents a simple, practical decision support tool that can support future implementations of WLC in practice. The research question considered in this study is:

Where, and how, should real-life job shop complexities be handled within the Workload Control concept?

The remainder of the paper is organised as follows. Section 2 provides a review of the relevant WLC literature before Section 3 outlines the decision framework. Section 4 describes the research approach taken in the case study, which is followed by an overview of the case study company in Section 5. The results are presented in Section 6, with a discussion and concluding remarks in Section 7. This final section includes implications for the theoretical development of the WLC concept to improve its applicability to real-life job shops, managerial implications and future research directions.

2. Theoretical Background

The WLC concept was originally developed in the 1980s (e.g. Bertrand and Wortmann 1981; Bechte 1988; Hendry and Kingsman 1989). Since then, many articles with a theoretical focus have followed. Simulation studies have demonstrated that WLC has the potential to improve performance (Thürer et al. 2011); however, there have been few recent successful real-world implementations (Stevenson et al. 2011; Soepenberget al. 2012b). Three papers have explored practical issues associated with the WLC concept. First, Hendry et al. (2008) identified 17 issues that affect WLC implementation relating to the manufacturing process, the market/customer, the flow of information, WLC system requirements and embedding WLC within organisations. For each issue, they proposed appropriate responses for a capital goods company and a subcontractor. They also identified research gaps relating to the practical application of WLC. Second, Stevenson and Silva (2008) examined how WLC had to be refined for implementation in two companies and proposed refinements. Finally, Hendry et al. (2013) reported on a successful implementation of WLC that led to improvements in lead-times, due date setting, delivery performance, and quality. It confirmed the importance of many of the implementation issues and verified many of the responses proposed in the earlier work by Hendry et al. (2008). However, there remains a need for further empirical research that addresses the practical complexities of real-life job shops when implementing WLC. Many of these complexities will require other considerations than load balancing. Section 2.1 will briefly outline the WLC concept, focusing on its original

load balancing considerations. For a more extensive review of the WLC literature in general, we refer the reader to Thürrer et al. (2011). Section 2.2 then identifies complexities that are present in real-life job shops that require other considerations to enable low and controlled workloads on the shop floor.

2.1. Workload control (WLC) and its traditional load balancing considerations

Figure 1 illustrates the relationships in the WLC concept between: the job (pre-shop) pool and the shop floor; input control decisions (job acceptance/due date assignment, job release and priority dispatching); and output control measures (medium term, short term and online capacity adjustments). The order entry decision relates to the acceptance/rejection of orders. If an order is accepted, a due date has to be determined before the order joins the pool. The order release decision then determines the sequence in which orders should enter the shop floor and when this should occur. Traditionally, release decisions are executed periodically, but Thürrer et al. (2012c) has shown that combining this with continuous order release can lead to further performance improvements. The final decision – dispatching – is made locally at each work centre on the shop floor based on some priority rule (Blackstone et al. 1982).

[Take in Figure 1]

Order release is generally seen as a key decision within the WLC concept (Oosterman et al. 2000). This decision should be complemented by dispatching on the shop floor, particularly when routings are long or complex (Soepenbergh et al. 2012a). Order release can be simplified greatly through effective control at the order entry stage (Thürrer et al. 2014b), but decisions at this preceding stage do not directly affect the shop floor workload. The framework presented in this paper therefore focuses upon the order release and dispatching levels. The reader is referred to Thürrer et al. (2013) for an overview of input control rules at the order entry level.

Order release decisions in the WLC concept focus on capacity in their check on the availability of resources before allowing orders to be released to the shop floor. It is generally assumed that materials are available when the order is considered for release (Land 2004), and similar assumptions will relate to complementary resources such as tooling. Order release involves a selection decision, i.e. which orders should be released from the pool, and a sequencing decision, i.e. the order in which jobs should be considered for release (Bergamaschi et al. 1997; Land 2004). Table 1 shows that the sequencing decision relates to

the timing function, whereas the selection decision relates to balancing the workload (Land 2004). However, there is a constant trade-off between satisfying the two functions. Normally, the most urgent orders would be selected for release first, but if an order does not fit the workload norms of all work centres, its release would be postponed. The remaining load gaps might be filled by less urgent orders, thus guaranteeing a certain level of load balancing (Land and Gaalman 1998). This load balancing function is essential when load reductions should not lead to drops in output. Within the theoretical concept, balancing loads across work centres and over time has been the only requirement in order to avoid both order waiting times and resource idle times.

[Take in Table 1]

2.2. . Complexities requiring other considerations than load balancing

Despite the focus of release and dispatching decisions in the WLC concept being on the trade-off between timing and balancing, many studies have referred to complexities in real-life job shops that require different order selections if the workload is to be controlled without incurring a loss of output. These selections also imply another trade-off with timing has to be considered. They may also conflict with the load balancing selections, although both aim to control workloads without incurring a loss of output. The complexities identified in the literature include:

- Sequence-dependent set-ups, where jobs are processed in a certain order to minimise the set-up time required between jobs. This is common in coating departments, where orders are sequenced to minimise colour changes between batches to avoid capacity losses due to higher set-up times. The issue of sequence-dependent set-ups has been considered in the context of WLC by Fernandes and Carmo-Silva (2011) and Thürer et al. (2012a, 2014a);
- Sequential batching (as distinguished from simultaneous batching by Hopp et al. (2000)), where several orders are processed one after the other to avoid set-ups and thus to reduce the loss of capacity available for processing. This is common in the metal industry, for instance when several orders requiring the same tooling would not require intermediate set-ups if the orders were processed successively;
- Simultaneous batching, where several orders are accumulated and processed together so that the capacity of a work centre is used to the full. This is common at work centres responsible for heat treatment processes where capacity is lost if the orders available for dispatching do not combine into a full oven load. These processes are commonly found in

job shops and in the semi-conductor industry where WLC is an important concept (Fowler et al. 2002);

- Nesting, which involves combining orders to minimise material wastage, e.g. so the maximum number of pieces can be cut from one sheet of metal. Combining orders saves not only on material but also on capacity, which is relevant for enabling WLC (Poppinga 2011). Nesting is commonly encountered in the shipbuilding, garment manufacturing, metal cutting and electronics industries (Israni et al. 1985);
- Assembly, which implies that components or sub-assemblies are produced separately before converging on a final assembly operation. A synchronised flow is required to make the right combinations of components available for assembly at the same time. Otherwise, some of the capacity of the assembly operation may be lost. This creates an additional complexity for WLC (Thürer et al. 2012b);
- Unsynchronised shift schedules, which relate to differences in operating hours for successive work centres. For example, a work centre operating only one 8-hour shift might be supplying a work centre with a lower capacity/demand ratio and therefore operating three 8-hour shifts (Ernst et al. 2004). Starvation may result if the latter work centre is not provided with sufficient and appropriate orders before the end of the single shift.

A common characteristic of the above complexities is that, if they are ignored, they will lead to a reduction in the output that can be realised by a work centre. Only considering the above complexities at the dispatching decision level will generally require a high workload to be built up in order to allow for reordering the queue in front of a work centre. Considering them already at the order release decision level should normally allow for a lower workload, but only if orders still arrive in the right sequence at the relevant work centres. Finally, considering a complexity may lead to undesirable consequences at other work centres both upstream and downstream of the complexity if the ideal sequences at those resources differ from that where the complexity occurs. Batched operations may, for example, create irregular inflows for downstream work centres, which conflicts with their balancing requirements. This makes it less obvious that all complexities should be considered simultaneously at release.

Earlier theoretical studies on WLC have already shown that considering certain complexities at both the order release and dispatching decision levels is possible. For example, Henrich et al. (2004), Fernandes and Carmo-Silva (2011), and Thürer et al. (2014a) suggested different approaches to handling sequence-dependent set-up times. Handling set-ups centrally via order release mechanisms leads to restricted queues and, consequently, to a

decrease in the effectiveness of dispatching to fulfil other functions (Kim and Bobrowski 1995). Thus, in practice, sequence-dependent set-ups are often considered locally after release of the orders to the shop floor (Fernandes and Carmo-Silva 2011). Meanwhile, Van de Wakker (1993) and Bertrand and Van de Wakker (2002) conducted early research on WLC for assembly operations and, based on their results, Hendry et al. (2008) suggested two broad strategies for handling assembly orders: one based on coordinating the arrival of components for assembly through dispatching decisions at preceding operations; and the other based on coordinating the release times of components to the shop floor. However, none of these studies led to general guidelines for the consideration of complexities during either the order release or dispatching decision making processes, nor did they consider how to handle multiple complexities at once. This paper seeks to develop a more generic approach to handling complexities without detailing the issues that each possible complexity may generate in its specific practical context. It is also intended to be applicable to complexities not identified from the literature in this section.

3. A decision framework for handling complexities at release and dispatching

The previous section identified six complexities that may be encountered when implementing WLC in practice. These are examples of complexities that require solutions other than balancing in order to keep the workload low and to produce the necessary output. Like load balancing, they may also conflict with the timing function of WLC. This section develops a deductive decision framework based on the literature. It recommends the stage that complexities should be handled (i.e. order release or dispatching). The framework is based on two dimensions: (1) the typical position of the work centre where the complexity occurs within the routing of orders; and (2) the criticality of the complexity.

3.1. Complexity dimensions

3.1.1. Dimension 1 – The position of the complexity in the routing of orders

Despite the key role of order release decisions in the WLC concept, Breithaupt et al. (2002) indicated that typical downstream work centres should either be ignored or have limited impact when making order release decisions. Meanwhile, Henrich et al. (2004) concluded that it is difficult to control the workload when routings become long. More recently, Soepenberg et al. (2012a) claimed that a sole focus on order release control is not sufficient when routings are long or complex. They argued that the effectiveness of order release is limited when a work centre is typically positioned downstream in the routing of orders.

Hence, when a complexity occurs upstream, control should be at the release level as this can strongly affect the arrival process at upstream work centres. However, when a complexity occurs further downstream, increased attention should be given to control at the dispatching level. In the theoretical pure job shop model, where routings are completely random, it is not possible to identify typical upstream and downstream work centres; and it would be impossible to determine at which stage to consider the complexity. Job shops in practice however will normally have dominant flows (Enns 1995; Oosterman et al. 2000).

3.1.2. Dimension 2 – The criticality of the complexity

We define criticality as the impact that a complexity would have on the output of a production process if it was not considered while reducing the workload. It is preferable for highly critical complexities to be considered at all possible decision levels, whilst less critical complexities only require handling during dispatching decisions for downstream operations. The main question is *when* a complexity should be classified as ‘critical’. First, if it occurs at a structural bottleneck resource, then the complexity is clearly critical as it constrains the throughput of the entire production process (Godfrey et al. 1985; Enns et al. 2002). Goldratt and Cox (1984) proposed that bottleneck schedules should act as the ‘drum’ that determines the release schedule independently of the position of the bottleneck in the routing of an order. Due to uncertainties that can occur during the flow of an order, dispatching might be needed to correct or further improve the sequence at a downstream station (see Section 3.1.1 above).

The term ‘critical’ however goes beyond determining bottlenecks, as we defined criticality in terms of the impact a complexity has on output while reducing the workload. Even work centres operating below their capacity might not allow for sufficient workload reductions unless their complexity is considered in the release sequence. This is illustrated in Figure 2, which presents the relationship between the workload of a work centre and the output of the shop using curves that are related to those previously presented in the literature as *clearing functions* (Missbauer 2011), and which have also been empirically derived and termed *logistic operating curves* (Nyhuis et al. 2009).

The relationship without considering a complexity at order release is indicated as a solid curve in Figure 2. In this case, a bottleneck work centre might be required to run at a high workload, represented by point X, in order to guarantee sufficient shop output. Reducing the workload would lead to a shift towards point Y, which will probably be undesirable due to its effect on output. Hopp and Spearman (2000) showed that improved release policies can avoid unnecessary starvation which will increase output, as represented by the dashed curve in

Figure 2. An improved release policy could enable a workload reduction without a loss in shop output, e.g. as represented by a shift from point X to point X'. In contrast, a non-bottleneck work centre might already operate at point Y as less output has to be produced. However, on this part of the curve, output will be very sensitive to small workload reductions. When it is important for the company to lower the workload further, this would imply moving to point Y', which can also be realised by an improved consideration of the complexity. The complexity would still be considered critical if output is very sensitive to the right sequence of orders, e.g. when set-up times are highly sequence-dependent.

[Take in Figure 2]

The work of Nyhuis et al. (2009) provides guidance for a quantitative estimation of the relationship for specific work centres in a practical context. But in situations with many complexities, the strength of the relationship between output and workload should be estimated by experts in a case-specific situation

To conclude, if complexity arises at a work centre that is a bottleneck, then the complexity is considered to be critical as it will have a major bearing on the output of the shop if it is not handled appropriately. If the work centre is not a bottleneck but workload restrictions will force a specific sequence of orders, e.g. to fill a batch or decrease set-ups, then the complexity is also critical. Finally, if the work centre is not a bottleneck and sequencing jobs in a specific order is not required to maintain a sufficiently low workload, then the criticality is considered to be low. When no criticality is present, we might consider neglecting the complexity completely as, in Goldratt's words (Goldratt et al. 1986, , p.179): "an hour saved at a non-bottleneck is just a mirage". However, in job shops, careful consideration is required when identifying bottlenecks. Stevenson et al. (2011) found that many shops have bottlenecks that shift over time, which means that a regular review of the shop status may be important.

3.2. The decision framework

A 2x2 decision framework is presented in Figure 3. From the quadrants in the figure, it can be concluded that:

- If a complexity occurs upstream, it should be controlled at the order release level (whether it be of high or low criticality);
- If a complexity occurs downstream, it should be controlled at the dispatching level if the criticality is low and at both the release and dispatching level if the criticality is high.

[Take in Figure 3]

To use the framework, it is first necessary to identify the complexities present in a production process and the criticality of each. Then, the framework can be used to determine the required level of control, i.e. release and/or dispatching. Finally, personnel must explore how the complexities can be accommodated at the proposed control level. Clearly, there is a limit on the number of complexities that can be considered simultaneously in the release decision. When multiple complexities are present, they should be prioritised, e.g. according to their relative criticality. Finally, it should be noted that the framework simplifies its two dimensions to a bi-polar scale. In every specific context, managerial judgement is required to determine whether a criticality is qualified as being high or low or where to set the border between upstream and downstream. The framework is illustrated through an exploratory case study.

4. Research method

Our research question concerned where and how the practical complexities should be handled within the WLC concept. The previous section presented a framework to support the decision concerning *where* the complexities can be handled when implementing WLC. A case study has also been undertaken to evaluate the framework and to gain an insight into *how* the complexities can be handled. We chose to focus on a single, exploratory case as this allows us to go into more depth when evaluating the consequences of our new framework. Following the logic of Yin (2013), this is an appropriate choice when studying a new phenomenon in practice. The following subsection briefly describes the selection of the case study company before data collection and analysis procedures are outlined.

4.1. Case selection

It was important to select a small-to-medium sized MTO company for which WLC was considered to be a suitable concept (Henrich et al. 2004; Stevenson et al. 2011) and also a company where multiple practical complexities were present. The selected company was an ideal candidate as it wanted to reduce its workload, fulfilled all criteria for WLC suggested by Henrich et al. (2004), but ultimately could not apply the concept because of its complexities. The Company, in the north of The Netherlands, produces aluminium profiles mainly for European customers in the building and construction industry. It is medium sized: in 2012 the Company had an annual turnover of €50m and approximately 150 employees. Some products

are bespoke, whilst others are ordered repeatedly over the length of a contract. In 2012, the Company produced 14,609 tonnes of high variety aluminium profiles.

The Company experienced four of the complexities identified in the literature review: sequence-dependent set-ups; sequential batching; simultaneous batching; and an unsynchronised shift schedule. Nesting was not common, and only a very small percentage of orders required assembly. Further, no new complexities that would require other specific considerations for load reduction were identified. An in-depth study was conducted to evaluate the decision framework, to determine how to handle the complexities at the chosen control level, and to understand what the resulting problems would be. No changes however in terms of implementation have been made by the researchers.

4.2. Data collection

Data were collected over a six month period, with the primary researcher based full-time in the Company. The explorative, but in-depth nature of the work further justified adopting a single case study approach (Voss et al. 2002). Both quantitative and qualitative data were obtained, which improved the construct validity of the study (Voss et al. 2002). The use of multiple data sources helped to establish a strong chain of evidence (Karlsson 2009).

At the beginning of the study, open-ended interviews were held with the Head of Planning, four Shop Floor Managers and a Planner responsible for three large production departments where the complexities were found. The interviews were transcribed and stored in a database. This was supplemented by daily tours of the shop floor, with observations documented in a notebook. Shop floor data were readily available from an Enterprise Resource Planning (ERP) system that was facilitated by a barcode scanning system. Further interviews were conducted at later stages to focus on particular areas of interest, such as Planning Department trade-off decisions, e.g. relating to balancing the workload and releasing urgent orders. This led to an improved understanding of how release and dispatching decisions affected performance. There was extensive contact at this stage between the Primary Researcher and the Plant Manager.

4.3. Data analysis

The various forms of data were analysed to understand current performance and workload control challenges. The use of different data sources helped to increase validity through triangulation (Edmondson et al. 2007). For example, insights from the interviews were compared with the daily production figures and observations. Daily production data confirmed that there were high levels of WIP and fluctuating shop floor workloads, which

had been observed when walking around the shop floor. Data were also analysed to locate and evaluate the criticality of each of the four relevant complexities. In addition, data were used to understand how each complexity was handled in the current situation. The framework was then used to determine the appropriate control level. Potential new strategies for addressing the complexities were discussed with the key informants and follow-up meetings were conducted to determine the appropriateness of the proposed solutions and identify factors that could influence the effectiveness of the solutions.

5. Case description

The Company comprises several large departments, including: extrusion, anodising, coating, packaging, and wrapping. Other smaller departments include: correction, thermal breaking, foiling, sawing, and mould fabrication & correction. Aluminium profiles are transferred between departments in cradles. The extrusion press is the first work centre in all routings; hence, all orders contribute to the load at extrusion. After extrusion, simultaneous batches are processed in an oven to create the necessary material hardness. The shop may be characterised as a job shop (Oosterman et al. 2000) as there is variability in processing times and routings, but a dominant flow exists whereby many products flow from extrusion to an oven and finally to packaging. According to Oosterman et al. (2000), this is a common appearance of job shops in practice. The routings often include three or four processes. As illustrated in Figure 4, the practical complexities present in the company can all be found in a typical four-step routing; therefore, the remainder of this paper focuses on the four work centres shown in Figure 4.

[Take in Figure 4]

In 2012, there was an average inflow of 95 orders per day. Processing times were highly variable, ranging from several minutes to almost a whole day. Hence, the load was high but there was also considerable variability. The Company's focus was on reducing WIP and increasing on-time delivery performance from 90% to 95%. Several improvement projects were underway to achieve this goal.

5.1. Planning procedures

The Planning Department consists of five people, including the Head of Planning – who oversees the whole process – and four other Planners who are responsible for: the extrusion press; packaging, anodising and coating; other smaller production departments; and

transportation. The order lead-time depends on the product family (i.e. a set of orders that follow the same or a similar routing) with the three main product families listed in Table 2. The order lead-time comprises the pre-shop throughput time and the shop floor throughput time. From Table 2, it is evident that the standard deviation of the order lead-time is high. This can be attributed to difficulties – related to the complexities – in controlling the workload, and it partly explains why the Company was struggling to meet its delivery promises.

[Take in Table 2]

The lead-times are now first estimated by the Head of Planning based on ERP system calculations. The ERP system uses a finite-capacity scheduling approach that actively searches for an ‘optimal schedule’. The Planning Department then considers the due date estimated by the ERP system, the available capacity and any due date proposed by the customer to determine the final agreed delivery date, building in some safety time where possible. Once agreed, the order arrives in the order pool. The ERP system then determines the latest possible start (LPS) date for each order at extrusion by backward scheduling from the agreed delivery date. This approach is consistent with a push system (Spearman et al. 1992), where the focus is on controlling throughput and measuring WIP. Hopp and Spearman (2004, , p.142) defined a ‘pull’ system as “one that explicitly limits the amount of work in progress that can be in the system”. Therefore, a pull system would focus on controlling WIP and measuring throughput. The Planning Department often neglected the effects of orders being considered for release to extrusion or downstream work centres. There appeared to be no communication between the Extrusion Planner and the other departments about which orders to release. Yet, many parameters beyond the extrusion press were relevant, including the order’s routings, relative urgency, alloy type, etc. These made planning a complicated task and caused high fluctuating workloads at the work centres.

6. Case analysis

This section evaluates the use of the proposed decision framework for each of the four complexities identified in the case study company. The source of each complexity, its consequences and the use of the framework to determine *where* to control the load are evaluated. In addition, the possibilities concerning *how* to accommodate the complexities within the release and dispatching decisions are assessed. Finally, some environmental factors that add to the trade-off dilemma within these decisions are discussed.

6.1. Sequence-dependent set-ups

Sequence-dependent set-ups were found in the coating department, where the Planner continuously searched for an optimal mix of colours to reduce set-up times. The load was controlled at the dispatching level only. There were two coating cabins: one for colours, and one for shades of white tint. All the orders were prepared for the coating operation on the same production line before it was split into two – one for each cabin. A sequence of orders was dispatched such that a white tint followed a colour, followed by a white tint, and so on. The resulting buffer in front of the cabins allowed enough time to clean one cabin while orders were getting coated in the other. The cabins needed to be cleaned between each colour change; the time required was dependent on the degree of colour change. Therefore, orders were dispatched in a sequence that minimised the total time take for colour change-overs. The Company coats products in over 500 different colours, which creates a large number of small orders.

The approach applied by the Company combined with the large number of colours led to a substantial workload buffer at this work centre to create an ‘optimal’ sequence. The buffer level also fluctuated significantly (see Figure 5), with an average buffer size of four days of work and a standard deviation of 1.5 days. In 2013, this work centre was required for 22% of orders. It was typically positioned in the downstream half of the routing, e.g. being the third of four work centres. Controlling the direct load for this work centre is difficult because of this positioning. Moreover, the work centre is regularly identified as a bottleneck. This makes the complexity critical as it has a major impact on output if it is not handled appropriately.

[Take in Figure 5]

Based on the proposed framework (see Figure 3), input control should be applied at both the release and dispatching levels. Ideally, orders would already be released onto the shop floor in a sequence that minimises set-ups (see Figure 6), thus reducing the load built up in front of the work centre to guarantee sufficient output. However, this approach had been found to be unsuitable due to uncertainty upstream of the coating work centre that was caused by a relatively high defect rate at extrusion. This perfectly illustrates the importance of additional control at the dispatching level in the framework. If orders were released in a sequence that minimised set-up times at the coating work centre and some orders were affected by quality problems at extrusion, this would have a knock-on effect on the output of

the Coating Department and, therefore, on the total process output. As a consequence, a small buffer in front of the coating work centre should be created to buffer against the risk of defects upstream. In order to improve the control of the load in front of the work centre, the sequence of orders should be considered at the release level based on broad colour categories (i.e. lighter colours could be released one day with darker colours released the next). Further improvement of the sequence could then be realised at the dispatching level by selecting from the inevitable (but smaller) direct load buffer in front of the department based on specific colour differences. It illustrates that elaboration of the question concerning how to address the complexity is particularly relevant for such a downstream critical complexity due to its combined consideration at the release and dispatching levels.

[Take in Figure 6]

6.2. Sequential batches

Sequential batching was used at the extrusion press where different orders that required the same mould could be combined into one sequential batch. Ideally, orders would still be planned according to their latest planned start (LPS) date, but sequential batching requirements often resulted in orders being pulled forward – sometimes by several weeks – to form a batch. This created an imbalance on the shop floor that could delay the progress of more urgent orders. The extrusion process is positioned first in the routing of all orders. As the extrusion press is sometimes a bottleneck and adds the most value to the end-product, guaranteeing sufficient output is important and makes this a critical complexity for the Company. According to the decision framework, the load should be controlled at the release level due to the upstream work centre position and the high criticality of the complexity. Since this is always the first work centre in the routing of an order, the released sequence should even fully determine the processing sequence to keep the buffer to a minimum. Dispatching should simply take place on a first-in-first-out (FIFO) basis. An example of an ideal release sequence is provided in Figure 7, where orders of a certain mould type (indicated by the shape in Figure 7) are sequenced for release successively.

[Take in Figure 7]

Within the release decision, the trade-off with urgency has to be addressed. Due to its effect on efficiency, the Plant Manager originally considered it infeasible to release any order separately if it could be batched. This was to the detriment of the timely completion of orders. Further, non-urgent orders produced early were stored in buffers on the shop floor, which

increased the likelihood of products degrading or being lost. This could result in unnecessary rework, which is more costly than an extra change-over. An alternative solution is necessary that reduces additional rework costs. One possible approach would be to create a timeframe for release from the pool that prevents non-urgent orders from being pulled too far forward for batching. This would mean sequential batches could still be formed within limits but without affecting the timing function too severely. A timeframe could be determined for each product family, e.g. dependent on the routing length of orders and on whether other complexities are present in the routing. Thus, even for this first operation in the routing, the answer to the question concerning how to address the complexity at release is not obvious.

6.3. Simultaneous batches

Simultaneous batching is required for the four heat treatment ovens. The ovens are located behind the two extrusion presses, with two ovens allocated to each press. The ovens can process batches independently of each other. The oven cycle time depends on the aluminium alloy, with almost 90% of orders using one of two alloys. Orders are transported from extrusion in batches of a full lorry before being processed in an oven. As a consequence, orders were sometimes split because a lorry was full and part of the order had to wait for the next cycle. This is not fully controllable at release because it is difficult to foresee when a lorry will be full, e.g. depending on the speed of the extrusion process and the size of profiles. In addition, the space in front of the ovens for buffering is limited; it can become overloaded and force the extrusion department to stop production.

This work centre was not considered to be a bottleneck, but provides an excellent example of why complexities at non-bottleneck operations can also be critical. An appropriate sequence (see Figure 8, where the size of the shape indicates the type of alloy) was essential to avoid blocking the previous operation due to the small buffer space, which would lead to a drop in output. Because the work centre is positioned relatively upstream in the routing of orders, the load should be controlled at the release level. This is consistent with current practice: the Company had designed its own solution for releasing orders in the right sequence to avoid an overload in the work centre buffer. Planning was restricted to releasing the alloys with the shortest cycle times at the start of the week and the larger cycle times at the end of the week. This seemed to be an appropriate approach to elaborating the complexity consideration at the release level.

[Take in Figure 8]

6.4. Unsynchronised shift schedule

The final complexity was an unsynchronised shift schedule. The coating work centre normally works for one shift per day while the immediate upstream and downstream work centres have three shifts. Not addressing this complexity could lead to a build-up of inventory in front of coating and an insufficient supply downstream to the wrapping process. This complexity, however, seemed non-critical as a load in front of the work centre was already needed to accommodate sequence-dependent set-ups. Nevertheless, if a substantial drop in load were achieved by reducing set-up times, this complexity could also become critical. The coating work centre is typically positioned downstream in the routing of an order and, in the current situation, control could be organised at the dispatching level. However, because all orders leaving the work centre go to wrapping, dispatching at the work centre itself has little effect. For this work centre, the sequence-dependent set-up time complexity issue is therefore prioritised above unsynchronised shift schedules, and this would also remain the case were the load reduced significantly.

Considering this complexity at dispatching, one step upstream of the coating work centre, may allow for the loads before coating to be reduced. The upstream work centre (the oven) runs for three shifts and, given that not all orders need coating, it should dispatch work in a sequence that supplies coating with an appropriate workload, given its one-shift schedule. Thus, work requiring coating should be supplied first and during the single shift of the coating operation. During the other two shifts, orders should be dispatched from the oven to the other work centres. However, this is not straightforward to realise because the oven produces in 2, 3 or 4 simultaneous batches a day, depending on the size of the aluminium profiles and the performance of the extrusion press. Consequently, some buffer before coating will be inevitable.

6.5. Consequences of applying the framework

The discussed application of the framework in this case study confirmed the choices concerning *where* to consider the complexities proposed by the framework. The answer to the question concerning *how* to consider the complexities could also be answered for the four individual complexities. But how all considerations can be combined is less obvious. Figures 6 to 8 illustrated how sequence-dependent set-up times, sequential batches and simultaneous batches all have different ideal release sequences for orders from the pre-shop pool. Each

requires a unique sequence of orders. In addition, LPS dates and the load balance should also be considered in determining the release sequence. This makes it very difficult to satisfy all three complexities at once.

A logical solution seems to be to prioritise the complexities according to their potential impact on the output of the process. In the case study company, sequential batching at extrusion is considered the most critical issue due to its high impact on the overall process output combined with its impact on the amount of value-adding activity. This implies minimising set-ups by releasing orders together or sequentially when they require the same mould. To serve the timing function of release, this batching should only relate to orders that fall within a pre-defined time window per product family, although this can be considered a soft planning rule, i.e. breakable in certain circumstances. A further hierarchy of complexities can be created with simultaneous batching and sequence dependent set-up times being successively considered at release if this does not violate the extrusion sequence severely. To reflect the criticality of simultaneous batching, alloys with large cycle times should still be sequenced towards the end of the week in order to fill batches in front of the ageing ovens efficiently. This should be a strict rule that cannot be broken without the permission of higher level management, as there is the potential for blocking the extrusion press, which would have a direct impact on the output of the shop. To reflect sequence-dependent set-up times at the coating work centre, the release of orders could be subjected to soft restrictions to create broad colour categories. This should be sufficient to keep the buffer needed for dispatching the final right colour sequence within limits.

6.6. Environmental factors affecting trade-off decisions

The interviews in the Company revealed two factors that further add to the challenge of managing trade-off decisions:

- Rush orders disturb the control of the load, especially if they are routed through work centres with practical complexities. If a rush order passes through coating, it faces three highly critical complexities, where it might affect the planned sequence. Considering rush orders by giving them priority in dispatching rules on the shop floor may therefore be disruptive. However, if improved control could result in a lower workload, it may be sufficient to account for rush orders at release as part of the timing considerations;
- The Company had a reduced order book during part of the research period, but because the initial work centre is so value-adding, management ensured it was highly utilised. Besides, it was only if the order book became extremely small that the number of shifts would be

reduced. As a result, many non-urgent orders are released early, processed at the first work centre and stored in downstream buffers. Instead, as the criticality of complexities decreases in the case of reduced order books, the timing function (i.e. the LPS date) should temporarily be given greater emphasis during release decisions.

In summary, Figure 9 illustrates the positioning of the four complexities in this case within the decision framework, while an overview of the four complexities is given in Table 3 along with a summary of the proposed solutions.

[Take in Figure 9 & Table 3]

7. Discussion and conclusions

This paper began by asking: where, and how, should real-life job shop complexities be handled within the Workload Control concept? A simple, practical framework (see Figure 3) was developed to provide a starting point for theory building and to help managers decide *where* a complexity should be handled. It is based on two dimensions: the typical position of a complexity in the routing of an order and the criticality of the complexity. A case study of a medium-sized MTO company – where four different complexities were present – demonstrated the utility of this framework (see Figure 9) and offered directions on *how* each complexity can be handled (see Table 3) as the single-case approach allowed for an in-depth consideration of the consequences. Moreover, we identified two environmental factors that further add to the challenge of implementing WLC in practice, i.e. rush orders and the size of the company's order book.

7.1 Implications for theory and management

The practical complexities analysed in this paper demonstrate that trade-off decisions for WLC are more complex than previously assumed. The WLC literature focuses on managing the trade-off between prioritising the most urgent orders and balancing shop floor workloads; but complexities including simultaneous batching, sequence-dependent set-up times, and unsynchronised workloads mean that the trade-off decision is not two-dimensional. These complexities require other solutions than balancing, which also conflict with the timing function. Figures 6-8 illustrated how each of the complexities in this case would lead to a different optimal sequence. According to the decision framework in Figure 9, most of these sequences should already be realised at the order release decision level, which will thus be

confronted with a nearly impossible reconciliation problem. It is expected that this challenge will be encountered in most companies that face multiple complexities.

As a consequence, the traditional simple release procedure of the WLC concept – which sequences orders based on their urgency and then realises the trade-off with balancing by selecting only the orders from this sequence that would fit within the workload norms – will become much more sophisticated. As a solution, a hierarchical approach has been suggested and briefly elaborated on for this case, translating the most critical complexity into an objective function for order release, while complexities of lower criticality would form either strict or soft constraints. Another solution would be to look for synergy in sequences and give priority to sequences that contribute to multiple complexities simultaneously.

The application of the framework at the case study company uncovered a number of lessons that are of general interest for researchers and managers alike:

- 1) *Considering highly critical complexities that are positioned downstream at both the order release and dispatching decision levels can be important due to upstream uncertainties.* The sequence-dependence set-ups at coating in the case study presented in this paper showed that sequencing improvements at dispatching may allow for a softer consideration than optimisation at release;
- 2) *Applying the decision framework may help to avoid the tendency in practice of focusing on the sequence that is optimal for a single complexity.* In optimising the sequential batches for extrusion, the case study company neglected the timing function of release. Urgent orders were combined with extremely non-urgent orders to create needless downstream congestion. Application of the framework helped to identify the need for trade-offs and a timeframe was suggested to restrict the potential to pull forward non-urgent orders;
- 3) *Non-bottlenecks can still be critical and thus require consideration when determining the release sequence where possible.* The non-bottleneck work centre for heat treatment in the case study company, which required simultaneous batching, forced the release of an appropriate selection of orders – otherwise, the workload in front of the work centre may have become too high and exceeded the available buffer space. This example showed that criticality considerations should extend beyond the work centre itself. In this case, the previous work centre in the routing of many orders was a bottleneck. Thus, a higher workload might have caused this work centre to be blocked meaning that the total process output of the shop would still be affected;
- 4) *Once a buffer in front of a work centre has been created to allow for the re-sequencing of orders via dispatching, the same buffer can also be used to fulfil the needs of other*

complexities. In this case, the downstream coating work centre would require a buffer to provide the sequencing possibilities necessary to reduce sequence-dependent set-up times. As a consequence, the same buffer could be used to select the right orders to soften the effect of the unsynchronised shift schedule at coating for consecutive operations;

- 5) *Consideration of complexities by dispatching rules should take place before the relevant operation is reached*. In this case, dispatching at the coating work centre, which operates for a single shift, would not help to reduce the buffer in front of coating. In general, dispatching in a certain queue will not be effective at reducing the length of the queue itself. It will only avoid needless capacity losses at the next work centre(s). Therefore, pre-selecting the right orders at work centres positioned further upstream should avoid the need to build up this buffer. This selection has similarities with optimisation at release, but it will be a more effective solution for downstream operations as the sources of uncertainty will already have been passed;
- 6) *The trade-off between timing, balancing and complexity considerations is not a static issue, but one that changes over time*. In this case, a time period with a reduced order book temporarily favoured giving higher priority to timing considerations. As all other considerations focus on reducing output losses, they are less relevant in these periods when the order book does not require a high output.

7.2. Limitations and future research

A number of limitations to this research should be noted. The framework was only evaluated using one company; hence, further research is needed to improve the generality of the findings. The nesting and assembly complexities identified from the literature were not present in this case. This however is not necessarily a problem as the framework is intended to be generic. It is independent of the specific type of complexity in terms of its suggestions concerning where to apply control. However, assembly in particular may be expected to lead to different solutions to those seen in this case as it requires the coordination of parallel flows. In addition to exploring other cases, such as with nesting and assembly complexities, it would also be helpful to consider cases with fewer complexities so that each can be isolated and examined in more depth.

The number of complexities present in our case and the sophistication required to consider them together during the release decision does not allow for the rapid implementation of the proposed solutions. Flexible software should first be built to support decisions before

subsequent studies examine cases where solutions to the complexities have been implemented to build on the findings of this paper.

Finally, future research could also extend the decision framework by including the third input control level to consider the practical complexities encountered when quoting due dates and accepting/rejecting orders. However, only the release decision can ultimately prevent workloads from building up on the shop floor and only dispatching decisions can correct for the inevitable uncertainty incurred during the progress of orders on the shop floor.

8. References

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List of Tables and Figures

<i>Order Release Element</i>	<i>Timing Function</i>	<i>Load Balancing Function</i>
Sequencing	x	
Selection		x

*Table 1: Function Served by Each Element of the Order Release Decision Making Procedure
(from Land, 2004)*

Product Family	Pre-Shop Lead Time (days)	Avg. Shop Floor Lead Time (days)	Avg. Total Lead Time (days)	St. Dev. of Total Lead Time (days)
Group 1	12	4	16	10
Group 2	15	9	24	13
Group 3	14	8	22	11

Table 2: Order Lead Times per Product Family in the Case Study Company (Data from 2012)

<i>Practical Complexity</i>	<i>Description</i>	<i>Input Control Level</i>	<i>Proposed Solution</i>
Sequence-dependent set-up times	A specific sequence of orders based on colour differences reduces change-over times.	Release & Dispatching	Consider broad colour categories at release while determining the sequence at the dispatching level.
Sequential batching	Orders that require the same mould are combined at the initial work centre in sequential batches to reduce set-ups.	Release	Set a time window per product family to avoid non-urgent orders being pulled forward too far to create batches at the expense of more urgent orders.
Simultaneous batching	Orders that require the same cycle time at the heat treatment work centre are batched together in simultaneous batches.	Release	Reserve capacity at the end of the week for orders that have a long cycle time to reduce variation in the production flow for downstream work centres.
Unsynchronised shift schedule	Where a work centre operating in three shifts delivers to a work centre that operates in one shift.	Dispatching	Only dispatch orders from the upstream work centre with more shifts to the downstream work centre when the downstream work centre is working.

Table 3: Overview of Practical Complexities and Proposed Solutions in the Case Study Company

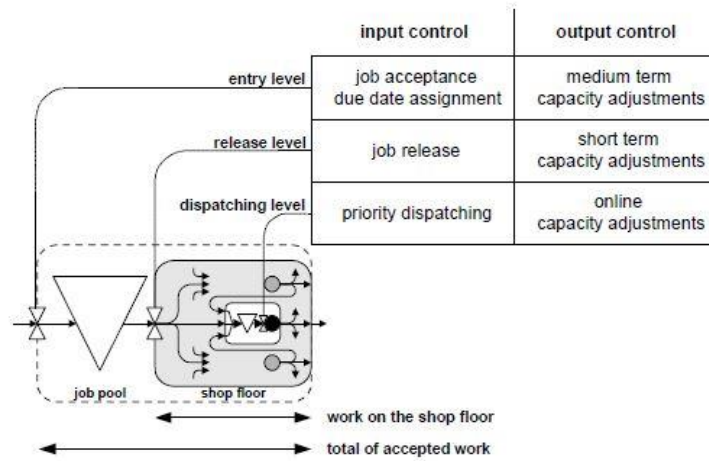


Figure 1: Input and Output Control Structure of the Workload Control Concept (from Land, 2004)

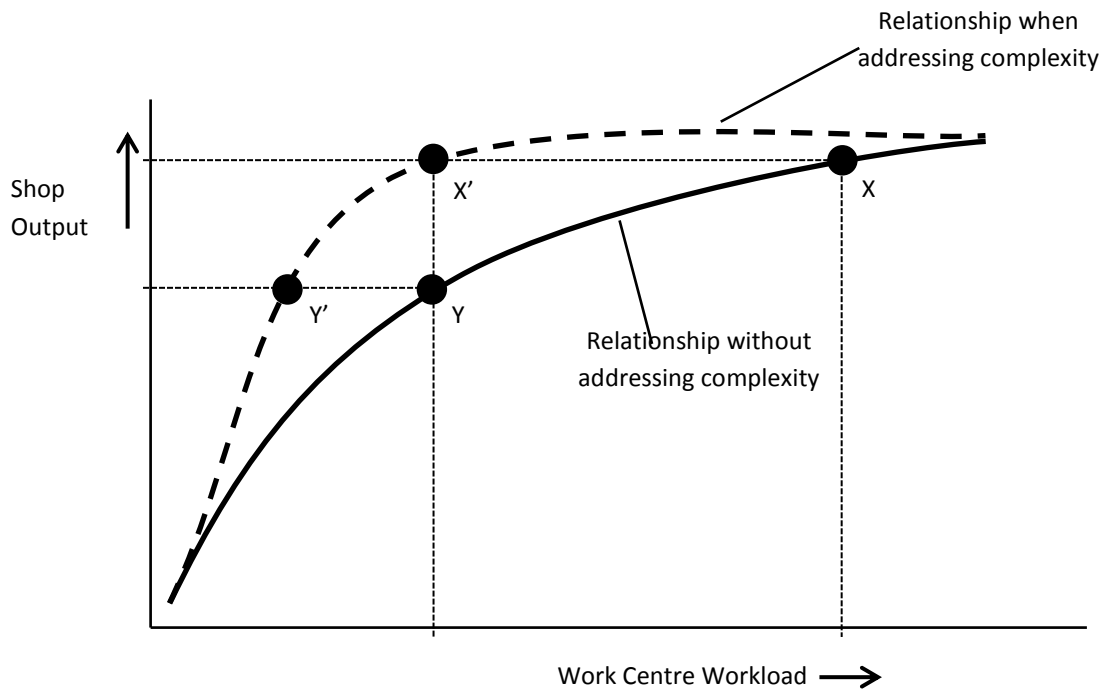


Figure 2: Determining the Degree of Criticality of a Complexity – Relationship between Work Centre Workload and Shop Output

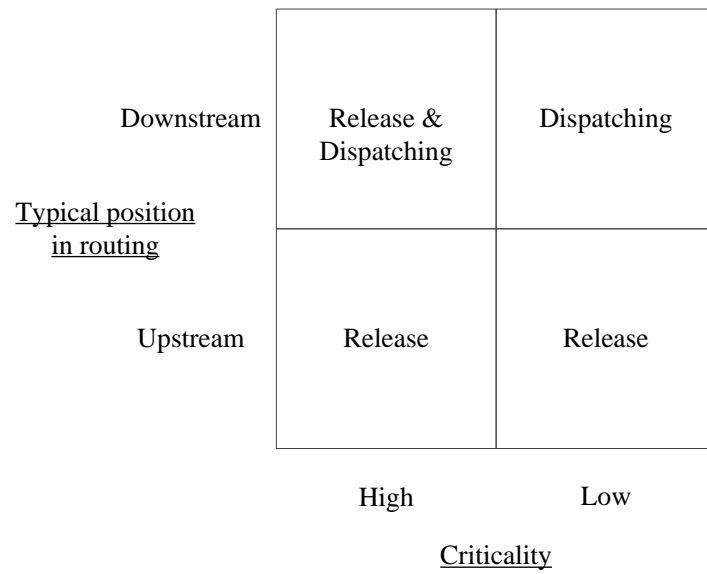


Figure 3: Conceptual Decision Framework for Determining the Control Level

1

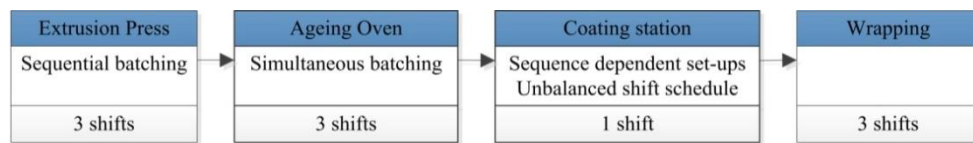


Figure 4: Occurrence of the Four Practical Complexities in the Routing of an Order

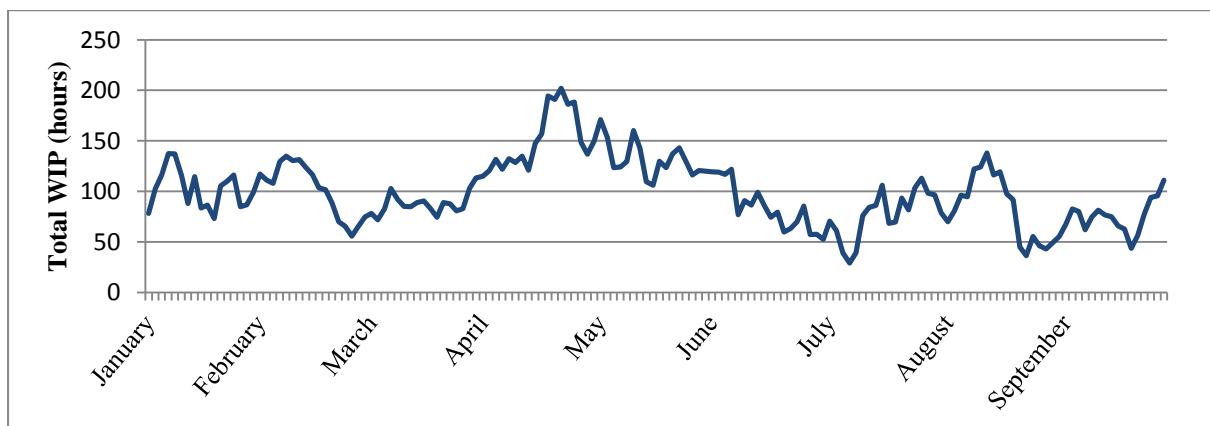


Figure 5: Daily Fluctuations of Workload in Front of the Coating Work Centre (2013 Data)

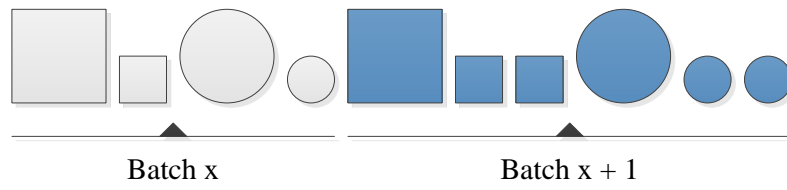


Figure 6: Sequence-Dependent Set-up Times – The Ideal Sequence of Orders Based on Colour Differences between Batches

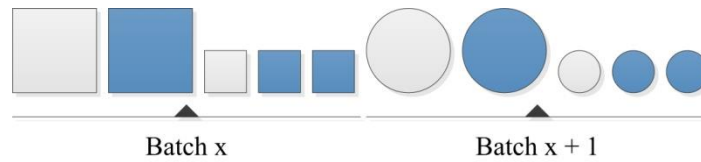


Figure 7: Sequential Batches – The Ideal Sequence of Orders Based on the Type of Mould

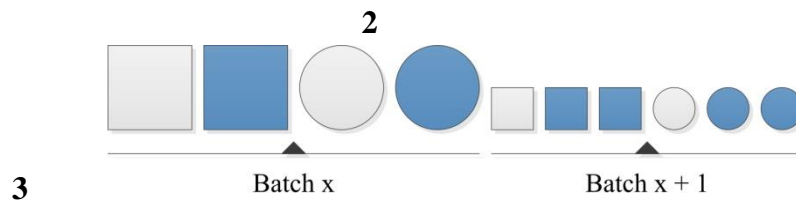


Figure 8: Simultaneous Batches – The Ideal Sequence of Orders Based on the Type of Alloy

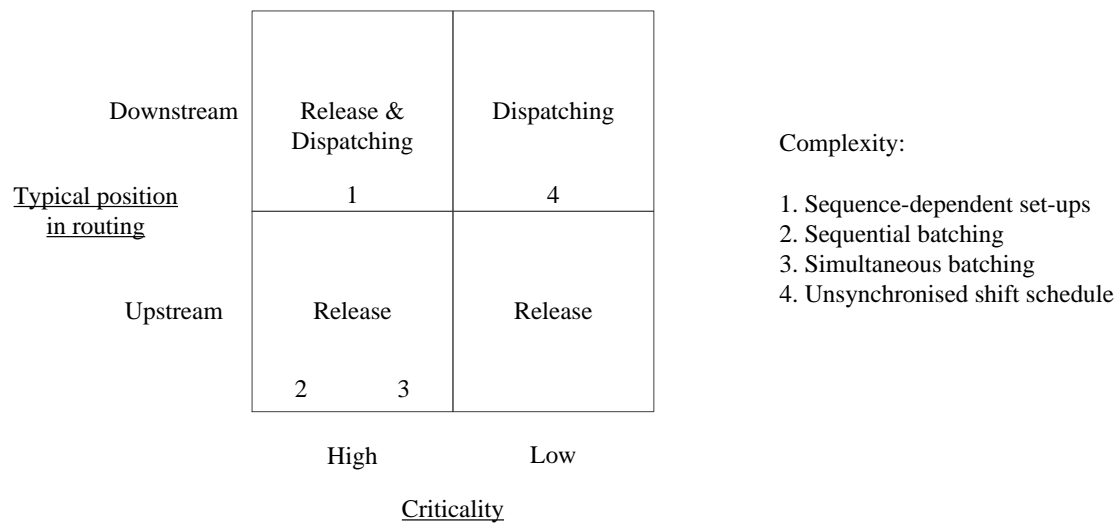


Figure 9: The Decision Framework Applied to the Case Study Company